Cluster AgeS Experiment (CASE): Dwarf Novae and a Probable Microlensing Event in the Globular Cluster M22

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ABSTRACT

We report the identification of a new cataclysmic variable (denoted as CV2) and a probable microlensing event in the field of the globular cluster M22. Two outbursts were observed for CV2. During one of them superhumps with $P_{sh} = 0.08875$ d were present in the light curve. CV2 has an X-ray counterpart detected by XMM-Newton. A very likely microlensing event at a radius of 2.′3 from the cluster center was detected. It had an amplitude of $\Delta V = 0.75$ mag and a characteristic time of 15.9 days. Based on model considerations we show that the most likely configuration has the source in the Galactic bulge with the lens in the cluster. Two outbursts were observed for the already known dwarf nova CV1.

Stars: dwarf novae – novae, cataclysmic variables – globular clusters: individual: (M22, NGC 6656) – Gravitational lensing

1 Introduction

The dense central regions of globular clusters (GCs) offer a unique opportunity for studies of dynamical processes in stellar systems. It is well established that even a small population of close binaries can drive the evolution of the entire cluster (Hut *et al.* 1992, 2003). It is expected on theoretical grounds that large numbers of cataclysmic variables (CVs) should be present in the central parts of GCs (Fabian *et al.* 1975; Hut and Paczyński 1984). Several tens of candidate cluster CVs have been reported over the last few years based on observations collected with the Chandra (*e.g.*, Hannikainen *et al.* 2005, Heinke *et al.* 2005) and XMM-Newton (*e.g.*, Gendre *et al.* 2003; Webb *et al.* 2004) telescopes. However, only a few CVs in GCs have been confirmed with spectroscopic observations. Similarly, there are only a few objects for which dwarf nova (DN) type outbursts have been observed (see Kaluzny *et al.* 2005 for more extended summary of the subject).

This contribution continues a series of papers devoted to the search for CVs in GCs based on the rich photometric data base collected by the CASE collaboration (Kaluzny *et al.* 2005). We report here the results for the cluster M22

Table 1: Positions of eruptive objects observed in M22

Name	RA(2000.0)	Dec(2000.0)	Distance from center
M22 CV1	$18^{\mathrm{h}}36^{\mathrm{m}}24\overset{\mathrm{s}}{.}66$	$-23°54'35\overset{''}{.}5$	$0\overset{'}{.}40$
M22 CV2	$18^{\mathrm{h}}36^{\mathrm{m}}02\overset{\mathrm{s}}{.}72$	$-23°55'24\overset{''}{.}6$	$5\overset{'}{.}51$
M22 microlens	$18^{\mathrm{h}}36^{\mathrm{m}}22\overset{\mathrm{s}}{.}40$	$-23°56'29\overset{''}{.}4$	$2\overset{'}{.}33$

(NGC 6656) which is located about one-third of the way between the Sun and the Galactic bulge. Two DN type outbursts were detected for the previously known variable CV1 and for the newly identified variable CV2. We have also observed a very likely microlensing event caused by a cluster star.

2 Observations and Search for Erupting Objects

The CASE project is conducted at Las Campanas Observatory. For the survey we used the 1.0-m Swope telescope equipped with a 2048×3150 pixel SITE3 CCD camera. With a scale of 0.435 arcsec/pixel the field of view was 14.8×23 arcmin^2. A fraction of the images of M22 was taken in a subrastered mode with a field of 14.8×15.6 arcmin^2. The analysis presented in this paper is based on a uniform set of trimmed images with a field of view 14.8×11.6 arcmin^2 (longer axis along E-W direction). The cluster core was located approximately at the center of the images.

The cluster was monitored during the 2000 and 2001 seasons. A total of 2006 images were taken through the V filter with exposure times 90-300s. In addition, we have obtained 390 images in the B filter with exposure times 140-300s. The number of V-band frames taken per night ranged from a few to 62. The median seeing was $1\overset{''}{.}41$ and $1\overset{''}{.}43$ for the V and B bands, respectively.

The photometry was extracted with the help of the *Difference Image Analysis Package* (DIAPL) written by Woźniak (2000) and recently modified by W. Pych. The package is an implementation of the method developed by Alard and Lupton (1998). The procedure used to search for possible "outbursting" objects is described in detail in Kaluzny *et al.* (2005). The search was based on the V band data collected on 71 nights for which at least one image with seeing better than $1\overset{''}{.}6$ was available. A reference frame for the V filter was constructed by combining 19 individual frames taken on the night of 2000 Sep 2/3. The seeing for that frame was $FWHM = 1\overset{''}{.}03$. Profile photometry, as well as aperture corrections for the reference images, was extracted with DAOPHOT/ALLSTAR (Stetson 1987). These measurements were subsequently used to transform the light curves from differential flux units into instrumental magnitudes. The final transformations onto the standard BV system were based on observations of several Landolt (1992) fields which were collected on one of the nights during which M22 was observed.

Searches for erupting objects in M22 led to the detection of three objects. In addition to the previously known DN CV1 (Anderson *et al.* 2003; Bond *et al.* 2005), we identified another DN (which we provisionally name CV2) and a probable microlensing event. The equatorial coordinates of these three objects, as well as their angular distances from the cluster center ($\alpha_{2000} = 18^h36^m24\overset{s}{.}2$, $\delta_{2000} = -23^{\circ}54^{'}12^{''}$, Harris 1996), are listed in Table 1.

3 Outbursts of CV1

The variability of CV1 was first noted by Sahu *et al.* (2001). They interpreted the May 1999 brightening episode detected on HST/WFPC2 images as a microlensing event. Subsequently Anderson *et al.* (2003) argued that in fact the variable is a CV and that the observed event was due to a DN type outburst. The outburst lasted about 25 days with an approximate amplitude of 3 mag, peaking at $I \approx 15$ mag. Two other outburst episodes, one in 2002 and one in 2003, were reported by Bond *et al.* (2005). For the event in 2002 only one exposure was obtained showing the variable at $I = 15.1$. During the 2003 episode the variable was observed at $I_{max} \approx 15.7$ mag, but the actual peak of the outburst was very likely not observed.

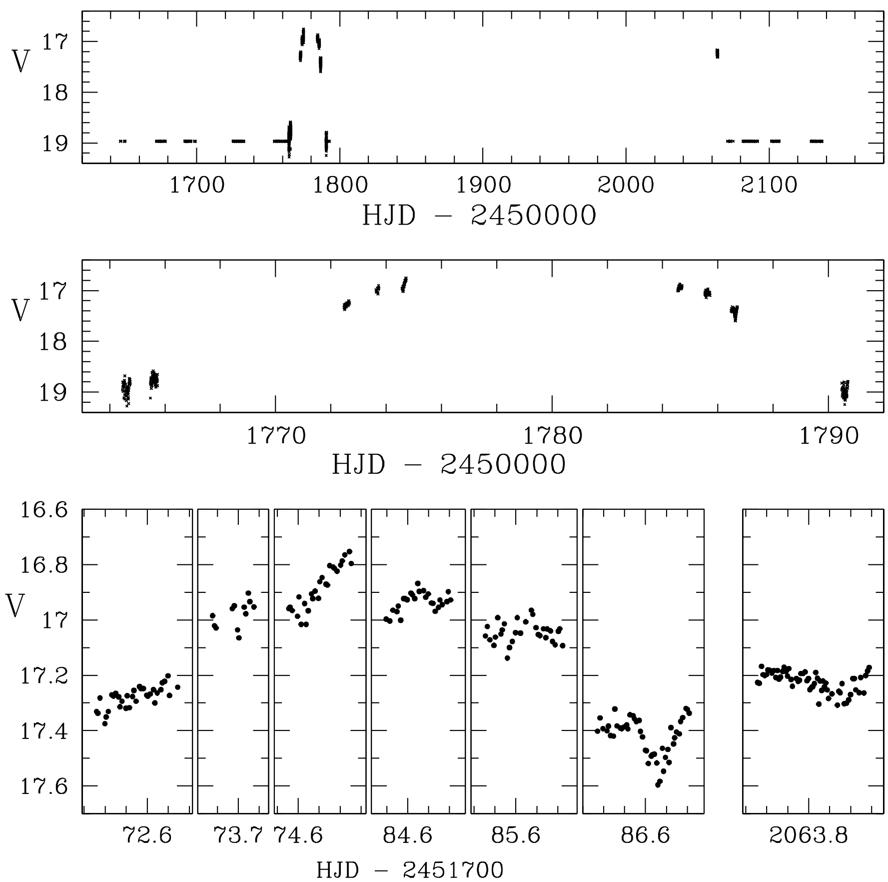

Fig. 1. Light curves of CV1: full span in the 2000-2001 seasons (upper panel), during the 2000 Aug/Sep outburst (middle panel) and nightly segmented during the outbursts (lower panels). In the segments small ticks are every 0.05 days.

As can be seen in Fig. 1 another two outbursts of CV1 were detected in our data. The first one occurred on August/September 2000 and lasted approximately 20 days. The observed maximum reached $V = 16.75$ mag, but we failed to cover the actual peak of the outburst. There is no evidence for the presence of superhumps in the light curve. The second outburst episode of CV1 in our data set occurred in 2001. On June 3, 2001 the variable had a mean magnitude of $V = 17.22$. Unfortunately, we observed the cluster on only one night during

this event, and observations collected seven days later showed that CV1 had already faded to a low state.

Our data taken together with the data of Bond *et al.* (2005) cover the observing seasons 2000-2004. A total of 4 outbursts were observed during that period suggesting that the average recurrence time is rather long, probably exceeding 150 days. The duration of the three outbursts with reasonably complete time coverage ranges from about 20 to about 25 days (Sahu *et al.* 2001; Bond 2005; this paper).

In Fig. 2 the location of CV1 during the 2000 eruption is marked on a color-magnitude diagram of M22. The cluster main sequence shows a noticeable spread due to the presence of significant differential reddening ($0.34 < E(B-V) < 0.42$ (Richter *et al.* 1999)). In the following analysis we use $E(B-V)=0.38\pm0.04$ for the cluster reddening. The variable had a mean color of $<B-V>=0.46\pm0.09$ near maximum light which implies an unreddened color of $(B-V)_0 = 0.08 \pm 0.13$. This is within the range of colors exhibited by DNe during outbursts (Warner 1995). We were unable to obtain reliable photometry of the variable on many images collected in the low state due to crowding effects. From archival HST/WFPC2 images (GO 8174 program) observed on 2000 June 28 we obtained $V_{min}=18.96$. The photometry was extracted with the help of HSTphot package (Dolphin 2000a,b). In Fig. 1 we adopt this value of V_{min} to mark all out-of-outburst observations of CV1.

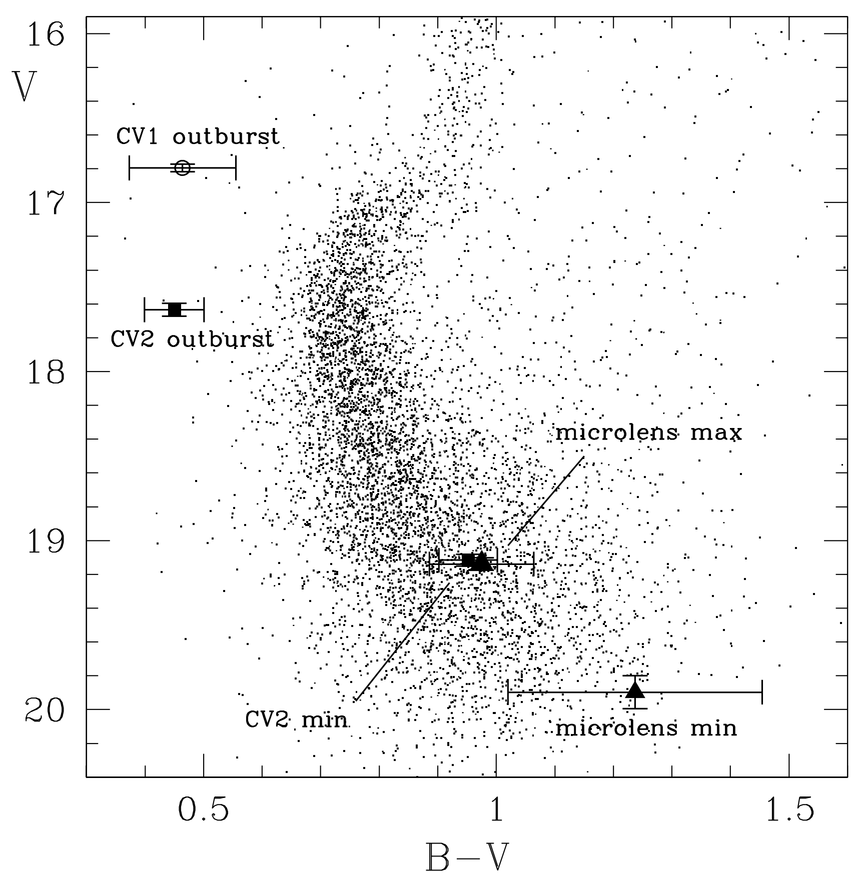

Fig. 2. Locations of observed cataclysmic variables and the microlensing event on the color-magnitude diagram of M22

4 Variable CV2

Fig. 3 shows the light curve of the newly detected candidate DN. A fading branch of an apparent outburst was observed during the period 2000 July 28-August 3. During that time the brightness declined from $V\approx 17.7$ mag to $V\approx 19.0$ mag. The main outburst was followed by an "echo" eruption lasting about two days. The light curve for the first three nights of observations covering the outburst (lower panel in Fig. 3) shows the presence of superhumps. Their shape and full amplitudes of ≈ 0.18 mag are typical for SU UMa type DN (Warner 1985). After subtracting nightly means from the light curve we calculated the power spectrum with ANOVA statistics (Schwarzenberg-Czerny 1996). The first two harmonics of the Fourier series were used in the fit. The resulting periodogram is shown in the upper panel of Fig. 4. The highest peak corresponds to a superhump period of $P_{sh} = 0.08875 \pm 0.00012$ days (127.80 ± 0.18 min), while the second peak is its subharmonic. The lower panel of Fig. 4 presents the light curve folded with P_{sh} and averaged in 0.05 phase bins. The orbital period of CV2 can be estimated using the empirical relation between P_{sh} and P_{orb} first noted by Stolz and Schoembs (1984). Using the calibration derived by Skillman and Patterson (1993) we obtain $P_{orb} = 0.08496$ d (122.3 min). This places

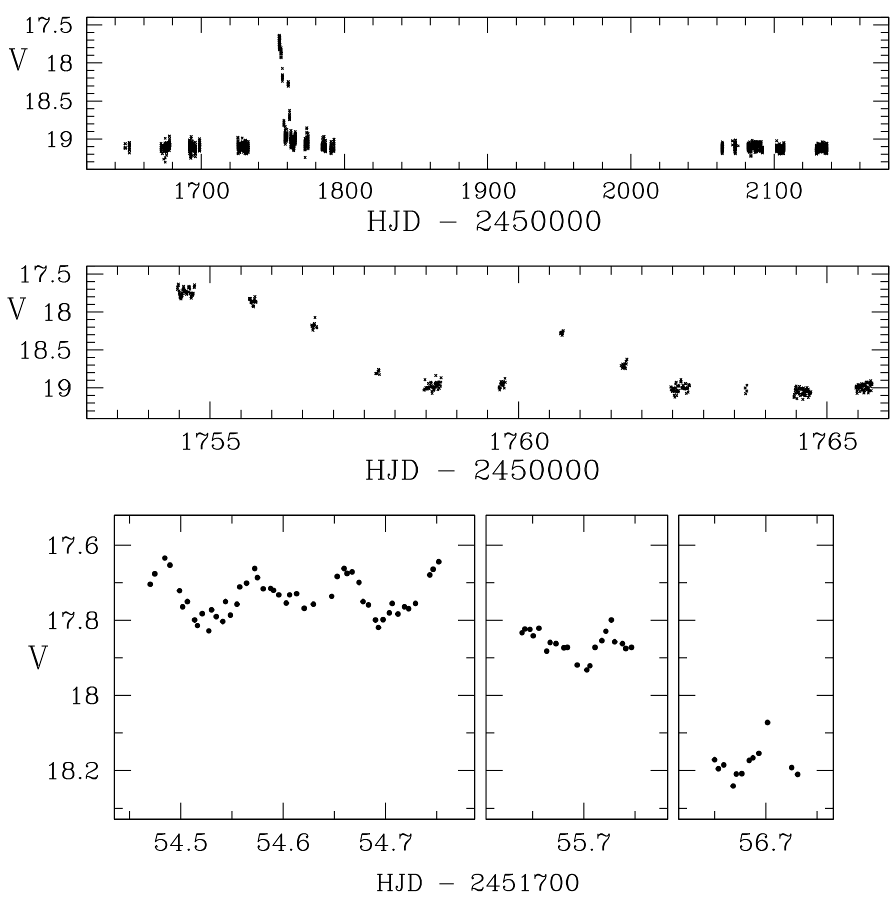

Fig. 3. Light curves of CV2: full span in the 2000-2001 seasons (upper panel), during the 2000 July/August eruption (middle panel) and nightly segmented during the superoutburst (lower panels). Note the presence of an "echo" outburst just after the superoutburst.

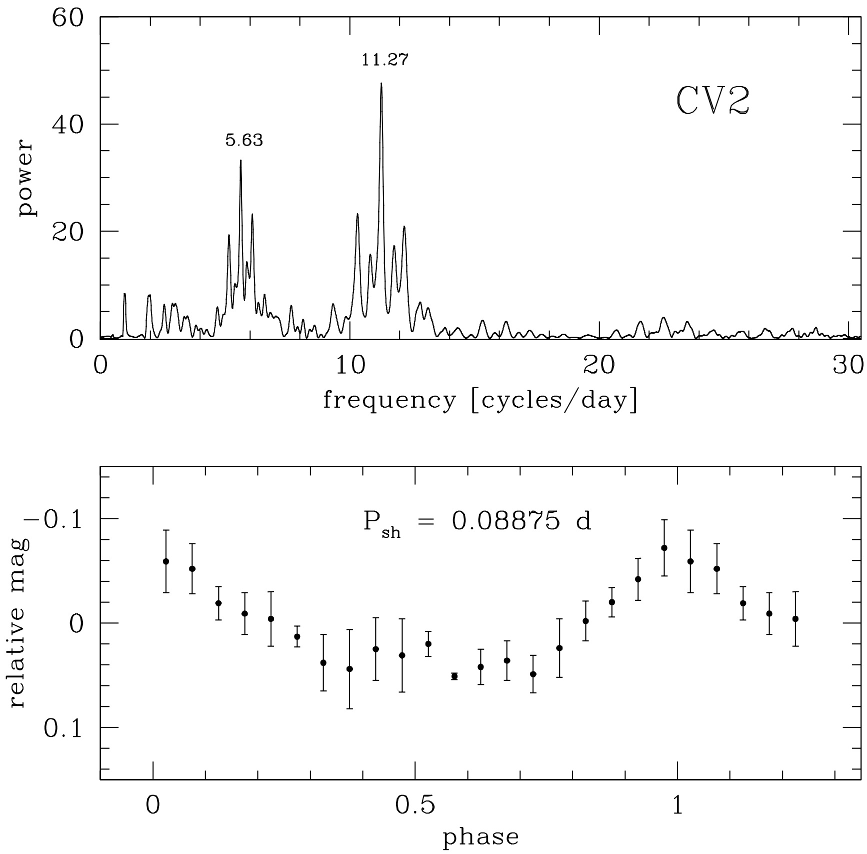

Fig. 4. Upper panel: the ANOVA power spectrum of CV2 of the JD=2451754-56 light curve of CV2. Lower panel: the light curve folded at frequency 11.267 cycles/day.

the variable at the lower edge of the gap observed in the distribution of orbital periods for CVs (Ritter and Kolb 2003).

Figure 5 presents finding charts for CV2 showing the variable in quiescence and in outburst. The variable is plotted on the cluster color-magnitude diagram in Fig. 2. We derive $B-V=0.95\pm0.05$ mag and $B-V=0.45\pm0.05$ mag for the low state and at maximum light, respectively. Assuming a reddening of $E(B-V)=0.38\pm0.04$ (Richter *et al.* 1999) we estimate the unreddened color at maximum light to be $(B-V)_0\approx0.07$ mag. Most DNe at maximum light have unreddened colors in the range $(B-V)_0=0.0\pm0.10$ mag (Warner 1976). The variable was observed at $V\approx19.0$ mag in quiescence. This brightness is consistent with the hypothesis that CV2 belongs to M22, despite being located at 3.9 core radii from the cluster center. Assuming cluster membership the variable has $M_V\approx5.5$ mag in quiescence (we adopt $(m-M)_V=13.5$ mag for M22, Harris 1996). This places CV2 in the range of absolute magnitudes observed for bright non-magnetic DN.

Further confirmation of the cataclysmic nature of CV2 comes from the X-ray observations of M22 obtained with XMM-Newton. Webb *et al.* (2004) published a list of 50 X-ray sources detected in the $30'\times30'$ field centered on the cluster. One of the sources, object #40, is a very probable counterpart of CV2. The equatorial coordinates of the X-ray object are $\alpha_{2000}=18^h36^m02\overset{s}{.}96$,

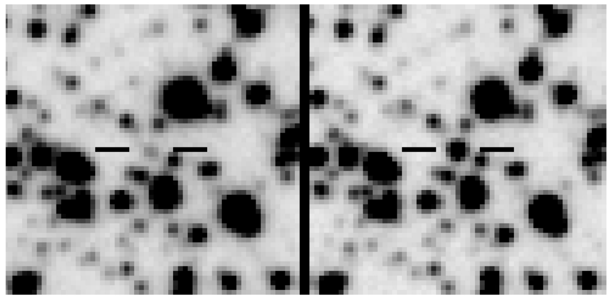

Fig. 5. Finding charts for CV2 showing the variable in quiescence (left) and during outburst (right). North is up and East is to the left. The field of view is $13''$ on a side.

$\delta_{2000} = -23^{\circ}55^{'}26\farcs42$, offset from the optical coordinates of CV2 listed in Table 1 by ($\Delta\alpha = 3\farcs6,\ \Delta\delta = 1\farcs8$), well within the $5''$ uncertainty circle of the X-ray source position. The XMM-Newton observations were obtained on Sep 19-20, 2000. That was 20 days after our last observation in the 2000 season and 45 days after the eruption of CV2. The measured count rate in the 0.5-10.0 keV band for source #40 was 2.74 times lower than that measured for source #36 associated with CV1. For CV1 Webb *et al.* (2004) give an unabsorbed flux of 9.8×10^{-14} erg cm^{-2}s^{-1}. Assuming that both CVs belong to the cluster at a distance of 3.2 kpc (Monaco *et al.* 2004) we can estimate the X-ray luminosity of CV2 during quiescence as $L_X \approx 4.4 \times 10^{31}$ erg s^{-1}. This value is consistent with X-ray luminosities observed for field non-magnetic CVs (*e.g.*, Baskill *et al.* 2005).

5 Microlensing Event in M22

Our search for erupting objects in M22 also led to the detection of a source which underwent one episode of increased luminosity. Its light curve is shown in Fig. 6. The source is located $140''$ from the cluster center in a relatively crowded region (see the chart in Fig. 7). The brightness of the object increased by ≈ 0.7 mag over 20 days. Around 2000 August 5 it reached a maximum of $V \approx 19.1$ and then faded to a constant level of $V \approx 19.9$ mag. On the cluster color-magnitude diagram (Fig. 2) the star is placed among the cluster main sequence stars. However, we note that at minimum brightness it is only marginally detectable on B images leading to a large uncertainty in the measured color. The variable is relatively red at the at the maximum light with $B-V = 0.97 \pm 0.09$ mag and $(B-V)_0 \approx 0.59$ mag. * This excluded possibility that the object belongs to DNs (Warner 1976). At minimum light we measured $B-V = 1.24 \pm 0.22$ mag what is consistent with a lack of any color change during an outburst.

The observed behaviour of the star is characteristic of a gravitational lens event. To check this hypothesis we use a 5-parameter model of a single lens event and fit a light curve of the standard form (Paczyński 1986):

$$F(t) = A(u(t))\ F_{\rm s} + F_{\rm b}$$

*According to Schlegel *et al.* (1998) the total reddening in the cluster direction amounts to $E(B-V) = 0.33$ mag. That implies that any stars located in the cluster field cannot be significantly more reddened than the cluster itself.

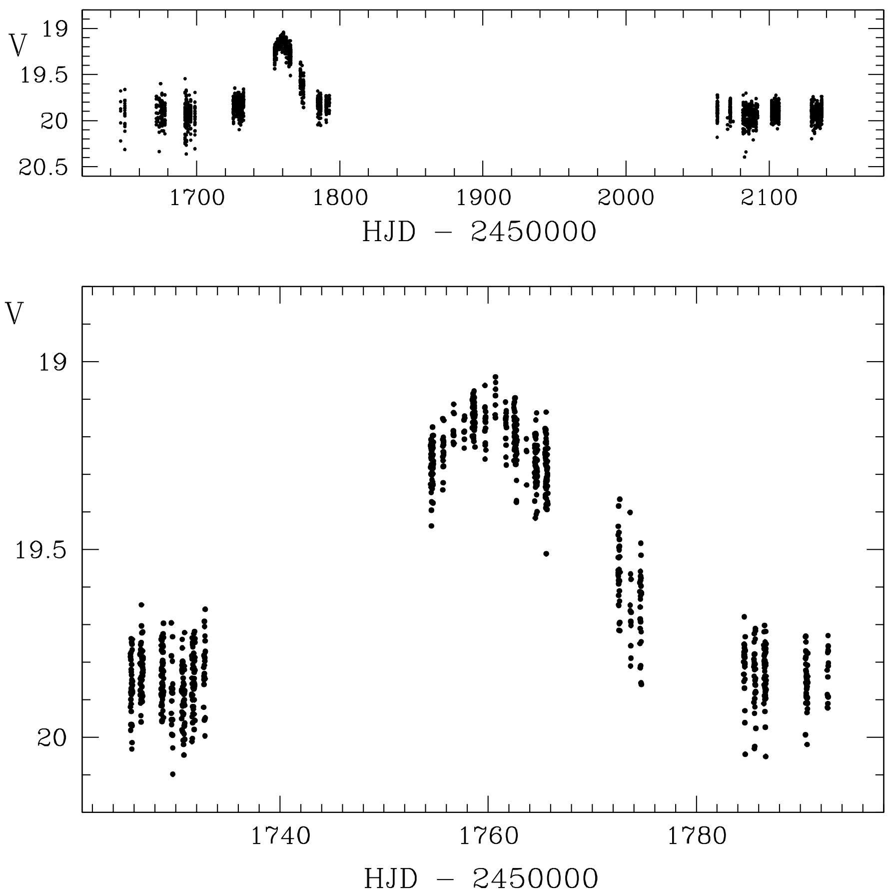

Fig. 6. Full span (top) and event (bottom) light curves of the probable microlens in M22.

$$A(u) = \frac{u^2+2}{u\sqrt{u^2+4}} \qquad u(t) = \sqrt{u_0^2 + \frac{(t-t_0)^2}{t_{\rm E}^2}} \tag{1}$$

where $F_{\rm s}$ is the (unmagnified) flux of the star undergoing lensing, $F_{\rm b}$ - the blended flux, t_0 - the epoch of maximum, $t_{\rm E}$ - a characteristic (*Einstein*) time of the event, and u_0 the impact parameter expressed in units of the Einstein radius. The Einstein radius for a lens of mass M located at a distance $d_{\rm L}$, and a source at a larger distance $d_{\rm S}$ is:

$$r_{\rm E} = \sqrt{\frac{4GM}{c^2}\frac{d_{\rm L}(d_{\rm S}-d_{\rm L})}{d_{\rm S}}} \tag{2}$$

where G is the gravity constant and c the speed of light.

We transform the measured stellar magnitudes V_i and their error estimates ΔV_i into flux units (F_i, σ_i) and fit the model minimizing χ^2:

$$\chi^2 = \sum_{i=1}^{N} \frac{(A_i\ F_s + F_b - F_i)^2}{\sigma_i^2} \tag{3}$$

where $A_i \equiv A(u(t_i))$.

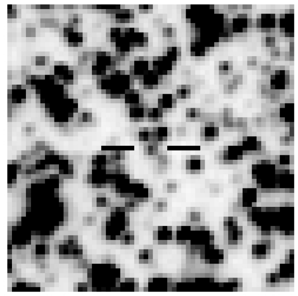

Fig. 7. Finding chart for the probable microlens in M22. North is up and East is to the left. The field of view is 13 $''$ on a side.

The fitted parameters, with source and blend fluxes converted back into stellar magnitudes $V_{\rm s}$, $V_{\rm b}$ are:

$$t_0 = 2451759.70^{+0.33}_{-0.34} \qquad t_{\rm E} = 15.^{\rm d}9^{+5.0}_{-1.1} \qquad u_0 = 0.54^{+0.02}_{-0.18}$$
$$V_{\rm s} = 19.92^{+0.62}_{-0.02} \qquad V_{\rm b} = 24.8^{+\infty}_{-4.0}$$
$$\chi^2 = 127 \qquad {\rm DOF} = 1923$$

The fit, shown in Fig. 8 is not well constrained due to the Woźniak and Paczyński (1997) degeneracy. The fitted parameters are highly correlated within the confidence regions in parameter space. The event can be fitted by a relatively shorter lasting and weaker amplification of a brighter source with a fainter blend as well as by a longer lasting and stronger amplification of a fainter source with a brighter blend.

The source and the lens can be located in the bulge, in M22, or anywhere along the line of sight. Since the large majority of objects of interest belong either to M22 or to the bulge, we shall consider primarily these locations. First we assume that the lens belongs to the cluster and compare the *a priori* relative probability of the source being in the bulge or in the cluster.

We adopt the distances $d_{\rm M22} = 3.2$kpc to the cluster (Monaco *et al.* 2004) and $d_{\rm B} = 8.0$kpc to the bulge. The Einstein ring projected into the source plane has a radius $\tilde{r}_{\rm E} = r_{\rm E}\ d_{\rm S}/d_{\rm L}$. Only sources within $\tilde{r}_{\rm E}$ from the observer - lens line are viable candidates for lensing.

For a rough estimation of the relative lensing probability we adopt a simplified model of the cluster assuming spherical symmetry and a density profile $n(r) \sim r^{-3}$ outside the core. The line of sight to the lensed source passes at $b_{\rm M22} = 2.17$pc from the cluster center while the core radius $r_{\rm c} = 1.30$pc (Trager *et al.* 1995). In our model the surface density of cluster stars is related to its space density along the line of sight:

$$N_{\rm M22} = \int_{-\infty}^{+\infty} n_0 \frac{b^3}{(b^2+x^2)^{3/2}}\ dx = 2 n_0 b \tag{4}$$

where n_0 is the 3D star density at a distance b from the cluster center. The probability of finding a cluster source within the Einstein radius from a lens of mass M is:

$$P_{\rm M22} = \frac{1}{N_{\rm M22}} \int_{-\infty}^{+\infty} dx\ n(x) \int_{x}^{+\infty} dy \left\{ n(y)\ \pi \frac{4GM}{c^2} \times \right.$$
$$\left. \times \frac{(d_{\rm M22}+y)(y-x)}{d_{\rm M22}+x} \right\} \approx N_{\rm M22} \frac{2\pi GM}{c^2} b_{\rm M22} \tag{5}$$

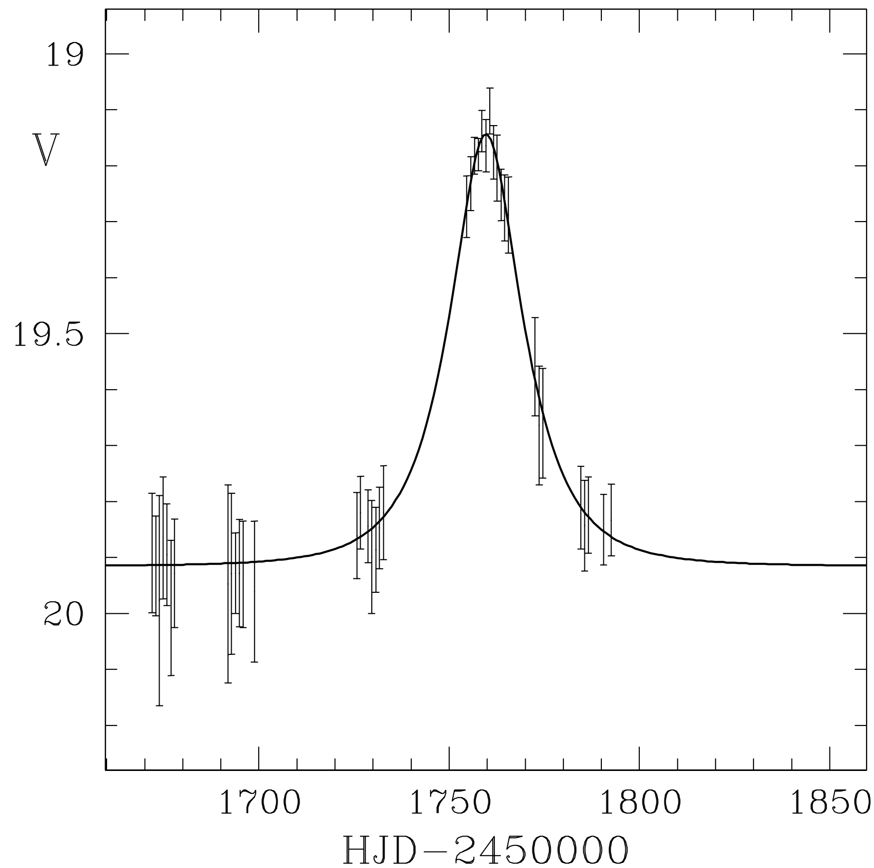

Fig. 8. The standard (5 parameter) binary lens model of the microlensing event. The data points were nightly binned for clarity of the plot.

where x and y are the lens and source positions respectively, measured along the line of sight. We approximate $(d_{\rm M22}+y)/(d_{\rm M22}+x)\approx 1$ and then solve the double integral analytically.

For a source in the bulge the lens position within the cluster is irrelevant, and one gets a probability of lensing:

$$P_{\rm B} = N_{\rm B}\frac{4\pi GM}{c^2}\frac{d_{\rm B}(d_{\rm B}-d_{\rm M22})}{d_{\rm M22}} \tag{6}$$

The relative probability of the lensed source belonging to the cluster is $P_{\rm M22}/P_{\rm B} = 9.04\times 10^{-5} N_{\rm M22}/N_{\rm B} \approx 5\times 10^{-4}$ where we use estimates of the surface densities of stars belonging to M22 and the bulge from Albrow *et al.* (2002).

Similarly, assuming that the source is located in the bulge, one can check the relative probability of finding the lens in the bulge or in the cluster. The calculations are analogous to those presented above, but the surface density of sources should be replaced by surface mass density of lenses. The line of sight passes at $\approx 12^\circ$ or $b_{\rm B}\approx 1.7$kpc from the bulge center. Calculations give

$$P_{\rm B} = \frac{2\pi G\Sigma_{\rm B}}{c^2} b_{\rm B} \tag{7}$$

$$P_{\rm M22} = \frac{4\pi G \Sigma_{\rm M22}}{c^2} \frac{d_{\rm M22}(d_{\rm B} - d_{\rm M22})}{d_{\rm B}} \tag{8}$$

where $\Sigma_{\rm B}$, $\Sigma_{\rm M22}$ stand for the surface mass density in the bulge and in M22, respectively, measured along the line of sight. The geometrical factors are of the same order, so $P_{\rm B}/P_{\rm M22} = 0.42\Sigma_{\rm B}/\Sigma_{\rm M22}$. Assuming that surface mass densities are proportional to the surface densities of stars we get $P_{\rm B}/P_{\rm M22} \approx 0.09$. The models of mass distribution in M22 and bulge suggest even an smaller value. Thus our estimates show that the location of the source in the bulge with lens in M22 is the most likely situation. The location of both objects in the bulge is ≥ 11 times less likely, while the location of both objects in M22 is ≈ 2000 times less likely. In the following we assume that the source is in the bulge and the lens in the cluster.

The proper motion of the lens relative to the source is dominated by the motion of the cluster as a whole (Gaudi 2002), $\mu_{\rm rel} = 10.9$ mas y^{-1} (Peterson and Cudworth 1994). The velocity dispersion of stars in M22, $\sigma = 11.4$ km s^{-1} (ibid.) corresponds to $\mu = 0.75$ mas y^{-1}, and the motion of stars in the bulge with velocity dispersion components $(\sigma_{\rm l}, \sigma_{\rm b}) = (93, 79)$ km s^{-1} (Han and Gould 1996) corresponds to $\mu \approx 2$ mas y^{-1}, so they can be neglected to simplify the analysis. By the definition of Einstein time we have $r_{\rm E} = d_{\rm M22}\mu_{\rm rel}t_{\rm E}$, which leads to the following mass estimate for the lens:

$$M = 0.14\ M_\odot \left(\frac{t_{\rm E}}{15.9\ {\rm d}}\right)^2 = 0.14^{+0.10}_{-0.02}\ M_\odot \tag{10}$$

where we neglect all sources of error except the uncertainty in the Einstein time fit.

6 Discussion and Summary

We have presented the results of a search for erupting objects in the field of the globular cluster M22. A new cataclysmic variable, CV2, which underwent a DN type superoutburst in 2000 was detected. Prominent superhumps with a period of 128 minutes were observed in the light curve during three nights. CV2 has an X-ray counterpart detected by the XMM-Newton telescope. The cluster membership of the object remains an open issue. Recent dynamical models of GCs (Heggie and Hut 2003) predict that close binaries should sink to the centers of the clusters due to encounters with neighboring stars. CV2 is located at a distance of 3.9 core radii from the center of M22. However, we note that there are several examples of close binaries located in outskirts of their parent clusters (eg. Bassa *et al.* 2003; Margon *et al.* 1981). The position of CV2 on the color-magnitude diagram of M22 and its observed X-ray luminosity are both consistent with the hypothesis that the variable is a cluster member. This issue can be easily settled by measuring the systemic radial velocity of the variable. The cluster itself has $V_{rad} = -149$ km/s which differentiates its stars from the background population. We also detected two DN outbursts for the previously identified variable CV1.

The search for erupting objects also led to the detection of a probable microlensing event in M22. It is located 2.3 arcmin from the cluster center and had an amplitude of 0.75 mag. We fitted the light curve to a 5-parameter model of a single lens event. The most likely geometry of the event places the source in the Galactic bulge and the lens in the cluster.

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